

LVD HIGHLIGHTS

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Abstract

The Large Volume Detector (LVD) in the INFN Gran Sasso National Laboratory, Italy, is a ν observatory mainly designed to study low energy neutrinos from the gravitational collapse of galactic objects. The experiment has been monitoring the Galaxy since June 1992, under increasing larger configurations: in January 2001 it has reached its final active mass $M = 1$ kt. LVD is one of the largest liquid scintillator apparatus for the detection of stellar collapses and, besides SNO, SuperKamiokande and Amanda, it is a charter member of the SNEWS network, that has become fully operational since July 1st, 2005. No gravitational core-collapse has been detected by LVD during 14 years of data acquisition; this allows to put an upper limit of $0.18 \text{ events y}^{-1}$ in our galaxy at the 90% C.L. The LVD tracking system allows the detection and the reconstruction of the cosmic muon tracks in a large fraction of the whole solid angle, in particular also horizontal tracks can be reconstructed. The results of the muon depth-intensity relation and of the flux of neutrino-induced muons are presented. Moreover, during 2006, the CNGS beam will start its operation: the performances of LVD as a beam monitor are described.

1 The LVD experiment

The Large Volume Detector (LVD), located in the hall A of the INFN Gran Sasso National Laboratory, Italy, is a multipurpose detector consisting of a large volume of liquid scintillator interleaved with limited streamer tubes in a compact geometry. It has been in operation since 1992, under different increasing configurations. During 2001 the final upgrade took place: LVD became fully operational, with an active scintillator mass $M = 1000$ t.

LVD consists of an array of 840 scintillator counters, 1.5 m^3 each, arranged in a compact and modular geometry; each of them is viewed on the top by three photomultipliers. All the scintillation counters are operated at a common threshold, $\mathcal{E}_h \simeq 5 \text{ MeV}$. To tag the delayed γ pulse due to n -capture, all counters are equipped with an additional discrimination channel, set at a lower threshold, $\mathcal{E}_l \simeq 1 \text{ MeV}$.

Other relevant features of the detector are: (i) good event localization and muon tagging; (ii) accurate absolute and relative timing: $\Delta t_{\text{abs}} = 1 \mu\text{s}$, $\Delta t_{\text{rel}} = 12.5 \text{ ns}$; (iii) energy resolution: $\sigma_E/E = 0.07 + 0.23 \cdot (E/\text{MeV})^{-0.5}$; (iv) very high duty cycle, i.e. $> 99.5\%$ in the last five years; (v) fast event recognition.

2 Supernova neutrino physics

The major purpose of the LVD experiment is the search for neutrinos from Gravitational Stellar Collapses (GSC) in our Galaxy (Aglietta et al., 1992).

2.1 Supernova neutrino emission

Indeed, in spite of the lack of a “standard” model of the gravitational collapse of a massive star, the correlated neutrino emission appears to be well established. At the end of its burning phase a massive star ($M > 8M_\odot$) explodes into a supernova, originating a neutron star which cools emitting its binding energy mostly in neutrinos and antineutrinos, almost equipartitioned among all species: $E_{\bar{\nu}_e} \sim E_{\nu_e} \sim E_{\nu_x} \sim E_B/6$ (where ν_x denotes generically $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ flavors). The energy spectra are approximatively a Fermi-Dirac distribution, with different mean temperatures, since $\nu_e, \bar{\nu}_e$ and ν_x have different couplings with the stellar matter: $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$. In the calculations presented in this work we assume a galactic supernova explosion at a typical distance of $D = 10 \text{ kpc}$, with a total binding energy of $E_b = 3 \cdot 10^{53} \text{ erg}$ and perfect energy equipartition $f_{\nu_e} = f_{\bar{\nu}_e} = f_{\nu_x} = 1/6$.

We also assume that the fluxes of ν_μ , ν_τ , $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ are identical; we fix $T_{\nu_x}/T_{\bar{\nu}_e} = 1.5$, $T_{\nu_e}/T_{\bar{\nu}_e} = 0.8$ and $T_{\bar{\nu}_e} = 5$ MeV.

LVD is able to detect $\bar{\nu}_e$ interactions with protons in the scintillator, which give the main signal of supernova neutrinos, with a very good signature. Moreover, it can detect ν_e through the elastic scattering reactions with electrons, $(\nu_e + \bar{\nu}_e)$ through charged current interactions with the carbon nuclei of the scintillator, and it is also sensitive to neutrinos of all flavors detectable through neutral currents reactions with the carbon nuclei.

The iron support structure of the detector (about 1000 t) can also act as a target for electron neutrinos and antineutrinos. The products of the interaction can exit iron and be detected in the liquid scintillator.

The signal observable in LVD, in different reactions and due to different kinds of neutrinos, besides providing astrophysical informations on the nature of the collapse, is sensitive to intrinsic ν properties, as oscillation of massive neutrinos and can give an important contribution to define some of the neutrino oscillation properties still missing.

2.2 Neutrino flavor transition

In the study of supernova neutrinos, ν_μ and ν_τ are indistinguishable, both in the star and in the detector, because of the corresponding charged lepton production threshold; consequently, in the frame of three-flavor oscillations, the relevant parameters are just $(\Delta m_{\text{sol}}^2, U_{e2}^2)$ and $(\Delta m_{\text{atm}}^2, U_{e3}^2)$.

We will adopt the following numerical values: $\Delta m_{\text{sol}}^2 = 8 \cdot 10^{-5} \text{ eV}^2$, $\Delta m_{\text{atm}}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$, $U_{e2}^2 = 0.33$ (Strumia & Vissani, 2005).

In the normal mass hierarchy (NH) scheme, neutrinos cross two so-called MSW resonance layers in their path from the high density region where they are generated to the lower density one where they escape the star: one at higher density (H), which corresponds to $(\Delta m_{\text{atm}}^2, U_{e3}^2)$ and the other at lower density (L), corresponding to $(\Delta m_{\text{sol}}^2, U_{e2}^2)$. Antineutrinos do not cross any MSW resonance.

For inverted mass hierarchy (IH), transitions at the higher density layer occur in the $\bar{\nu}$ sector, while at the lower density layer they occur in the ν sector.

The adiabaticity condition depends both on the density variation and on the value of the oscillation parameters involved. Given the energy range of supernova ν (up to ~ 100 MeV) and considering a star density profile $\rho \propto 1/r^3$, the L transition is adiabatic for any LMA solution values. Thus the probability to jump onto an adjacent mass eigenstate (hereafter called

flip probability) is null ($P_L = 0$). The adiabaticity at the H resonance depends on the value of U_{e3}^2 in the following way (Dighe & Smirnov, 2000) :

$$P_H \propto \exp [- \text{const } U_{e3}^2 (\Delta m_{\text{atm}}^2/E)^{2/3}]$$

where P_H is the flip probability at the H resonance.

When $U_{e3}^2 \geq 5 \cdot 10^{-4}$ the conversion is completely adiabatic (*ad*) and the flip probability is null ($P_H = 0$); conversely, when $U_{e3}^2 \leq 5 \cdot 10^{-6}$ the conversion is completely non adiabatic (*na*) and the flip probability is $P_H = 1$. We used in the calculation $U_{e3}^2 = 10^{-2}$, which is just behind the corner of the CHOOZ upper limit, for the adiabatic case and $U_{e3}^2 = 10^{-6}$ for the non adiabatic one.

For neutrinos, in the NH-*ad* case ν_e generated in the star arrive at Earth as ν_3 , so their probability to be detected as ν_e is $U_{e3}^2 \sim 0$. Thus, the detected ν_e come from higher-energy ν_x in the star that get the Earth as ν_2 and ν_1 . If the H transition is not adiabatic or if the hierarchy is inverted the original ν_e get the Earth as ν_2 and their probability to be detected as ν_e is $U_{e2}^2 \sim 0.3$.

For antineutrinos, in the NH case or in the IH-*na*, the $\bar{\nu}_e$ produced in the supernova core arrive at Earth as ν_1 , and they have a high ($U_{e1}^2 \simeq 0.7$) probability to be detected as $\bar{\nu}_e$. On the other hand, the original $\bar{\nu}_x$ arrive at Earth as ν_2 and ν_3 and are detected as $\bar{\nu}_e$ with probability U_{e2}^2 . In the IH-*ad* case the detected $\bar{\nu}_e$ completely come from the original, higher-energy $\bar{\nu}_x$ flux in the star.

In figure 1 we consider the inverse beta decay of $\bar{\nu}_e$ (the main interaction in LVD) and we show the energy spectra of the detected $\bar{\nu}_e$ in the case of no oscillation and in the case of adiabatic transition with NH and IH. In the case of oscillation, adiabatic, normal hierarchy, there is a contribution ($\sin^2 \theta_{12}$) of the originally higher-energy $\bar{\nu}_x$ which gives rise to a higher average neutrino energy and to a larger number of detected events. The ν_x contribution is even higher (~ 1) if the transition is adiabatic and the hierarchy inverted, because the MSW resonance happens in the $\bar{\nu}$ sector.

Another important contribution to the total number of events is also given by neutrino interactions in the iron support structure of the LVD detector. Given the rather high effective threshold (about 10 MeV) and the increasing detection efficiency with the neutrino energy, they are concentrated in the high energy part of the spectrum ($E_\nu > 20$ MeV). In figure 2 we show the contribution of $(\nu_e + \bar{\nu}_e)$ Fe interactions on the total number of events. For the chosen supernova and oscillation parameters they are about 17% of the total signal.

The expected number of events in the various LVD detection channels and in the different oscillation scenarios are shown in table 1.

Table 1: Expected results in the various LVD detection channels and in the mean energy of the detected $\bar{\nu}_e p$ events.

	No Oscillation	Non Adiabatic	Adiabatic NH	Adiabatic IH
$\bar{\nu}_e p$	346.	391.		494.
$\langle E_{\bar{\nu}_e} \rangle$ in $\bar{\nu}_e p$	25. MeV	30. MeV		37. MeV
CC with ^{12}C	8.	22.	29.	27.
CC with ^{56}Fe	22.	72.	95.	92.
NC with ^{12}C	27			

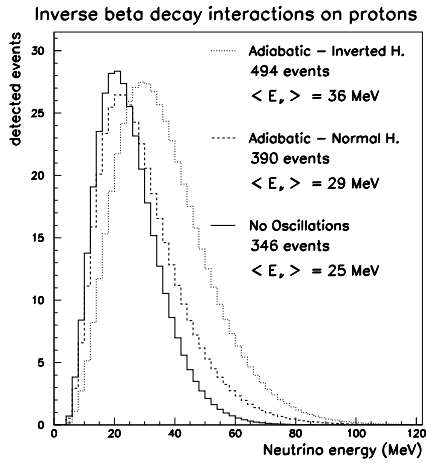


Figure 1: Neutrino energy distribution in the $\bar{\nu}_e$ interactions with p expected in LVD for three oscillation scenarios: no oscillation (solid line), adiabatic transition with NH (dashed), adiabatic transition with IH (dotted).

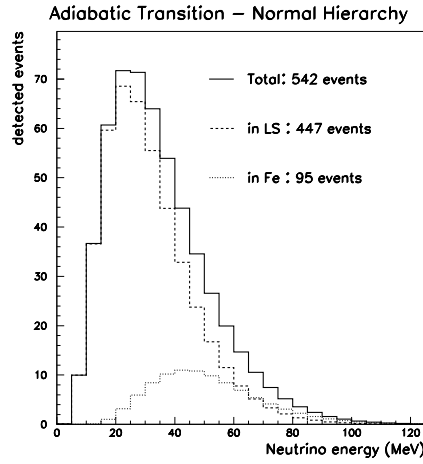


Figure 2: Neutrino energy distribution of the events occurring in the liquid scintillator (dashed), in the iron support structure (dotted) and their sum (solid) in the LVD detector.

2.3 Monitoring the Galaxy

LVD has been continuously monitoring the Galaxy since 1992 in the search for neutrino bursts from GSC ¹. Its active mass has been progressively increased from about 330 t in 1992 to 1000 t in 2001, always guaranteeing a sensitivity to gravitational stellar collapses up to distances $d = 20$ kpc from the Earth, even in the case of the lowest ν -sphere temperature.

In fig. 3 and 4 we show respectively the duty cycle and the average active mass, during the last 5 years. Considering just the last year (shaded areas) the average duty cycle was 99.98% and the average active mass 940 t.

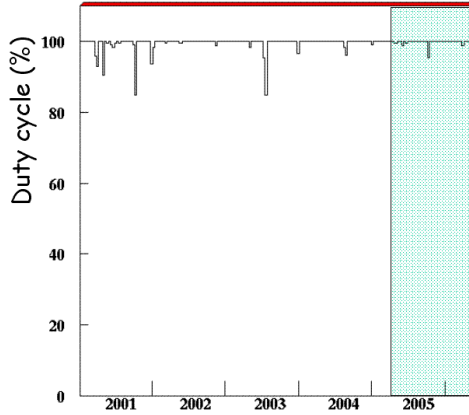


Figure 3: LVD duty cycle during the last 5 years of data acquisition.

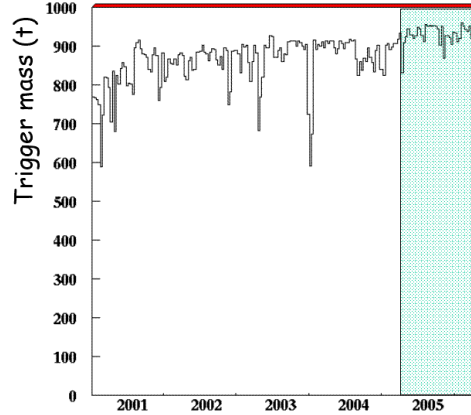


Figure 4: LVD active mass during the last 5 years of data acquisition.

All events are processed on the base of their time sequence, searching for cluster not compatible with a poissonian fluctuation of the background. A first selection consists in rejecting the crossing muon events and accepting only those with energy in the $[7 - 100]$ MeV range. After this selection cut we obtain a very stable counting rate $f_b = 0.3$ Hz. Each cluster is identified by its multiplicity m and its duration Δt (up to 200 s): the imitation frequency Fim (that is the frequency that a particular cluster $(m, \Delta t)$ is due to a poissonian fluctuation of the background f_b) is then calculated. The interesting candidates (those with $Fim < 1$ ev/year) undergo several consistency checks: (i) the topological distribution of pulses inside the detector has to be uniform; (ii) their energy spectrum is checked against the back-

¹The results of this search have been periodically updated and published in the ICRC Proceedings, since 1993 until 2005.

ground spectrum and (iii) the time distribution of the delayed low energy pulses (due to the 2.2 MeV gamma from the neutron capture) must follow an exponential law.

No significant signal has been registered by LVD during 14 years of data acquisition. Since the LVD sensitivity is higher than what is expected from GSC models (even if the source is at a distance of 20 kpc and for soft neutrino energy spectra) we can conclude that no gravitational stellar collapse has occurred in the Galaxy in the whole period of observation: the resulting upper limit to the rate of GSC, updated to April, 2006, at 90% C.L. is 0.18 events/yr.

2.4 SNEWS

The SNEWS (SuperNova Early Warning System) (Antonioli et al., 2004) project is an international collaboration including several experiments sensitive to a core-collapse supernova neutrino signal in the Galaxy and neighbour. The goal of SNEWS is to provide the astronomical community with a prompt and confident alert of the occurrence of a Galactic supernova event, generated by the coincidence of two or more active detectors. In addition the collaboration is engaged in cooperative work, such as the downtime coordination and inter-experiment timing verification, designed to optimize the global sensitivity to a supernova signal.

A dedicated process waits for alarm datagrams from the experiments' clients, and provides an alert if there is a coincidence within a specified time window (10 seconds for normal running). In July 2005, after a few years of tuning, the charter members of SNEWS (i.e., LVD, Super-K and SNO) together with the newly joined Amanda/IceCube, started the effective operation of the network, which means that the alert is really sent to the list subscribers, in the case of an at least two-fold coincidence (see *snews.bnl.gov* to get your own SN alert !).

Up to now, no inter-experiment coincidence, real or accidental, has ever occurred (except during a special high rate test mode), nor any core collapse event been detected within the lifetimes of the currently active experiments.

3 Cosmic Ray Physics

The scintillation counters are interleaved by a large acceptance tracking system made of limited streamer tubes ($1 \times 1\text{cm}^2$ cell' cross section): two staggered layers cover the bottom and one lateral side of the cluster of 8 scintilla-

tion counters. They are read out by 4 *cm* strips. The tracking system allows the detection and the reconstruction of the cosmic muon tracks in a large fraction of the whole solid angle, in particular also horizontal tracks can be reconstructed. The total acceptance of one LVD tower is about 350 $m^2 sr$. The tracking system has been operative since the beginning of the experiment (1992) until 2002. Seven million muon events have been detected and reconstructed during about 70000 *h* of live time for data acquisition. In the analysis we have used muon events with all multiplicities. The acceptances for each angular bin have been calculated using the simulation of muons passing through LVD taking into account muon interaction with the detector material and the detector response. As a result of the data processing the angular distribution of the number of detected muons $N_\mu(\phi, \cos \theta)$ has been obtained. The angular informations allow to derive the amount of rock crossed by the muons, given the knowledge of the Gran Sasso mountain profile. Thus, the so-called depth-intensity relation has been calculated, for a very large range of slant depths ([3 – 20] km *w.e.*), see figure 5. Two main components can be identified. The first one is dominant at slant depth up to 13 km *w.e.* and is due to conventional cosmic muons, i.e. high energy downward muons produced by π and K mesons in the atmosphere. When fitted with the formula $I_\mu(x) = A \left(\frac{x_0}{x}\right)^\alpha \exp^{-x/x_0}$ we obtain: $A = (2.17^{+0.12}_{-0.18}) 10^{-6} cm^{-2} sr^{-1} s^{-1}$, $x_0 = (1175 \pm 10) hg/cm^2$ and $\alpha = 2.07 \pm 0.03$. Those results are in agreement with those of the other underground experiments. Previous results were published in (Aglietta et al., 1998). The second is due to horizontal muons produced by neutrino interaction in the rock surrounding LVD. They are independent of the slant depth and thus they become observable when the atmospheric muon flux is suppressed by the large amount of rock. Their value is $(4.95 \pm 1.15_{stat} \pm 0.4_{syst}) 10^{-13} cm^{-2} sr^{-1} s^{-1}$.

4 CNGS beam monitor

The CNGS beam will start its operation during the summer 2006. It is a high energy ν_μ beam mainly devoted to study neutrino oscillation through the appearance of ν_τ at the LNGS. The LVD detector will act as a useful beam monitor (Aglietta et al., 2004). Two main kind of events will be detected: muons originated through charged current neutrino interaction in the rock upstream of the LNGS (about 120 per days at nominal beam intensity, see a typical events in figure 6) and the charged and neutral current interaction inside the apparatus (about 30 per day). The background due

to cosmic muons is negligible because of the clear time structure of the CNGS beam spill and the orientation of the events (mainly vertical for cosmics, horizontal for the CNGS ones). In one week of data acquisition a 3% statistical accuracy can be obtained, useful to check for the overall beam orientation.

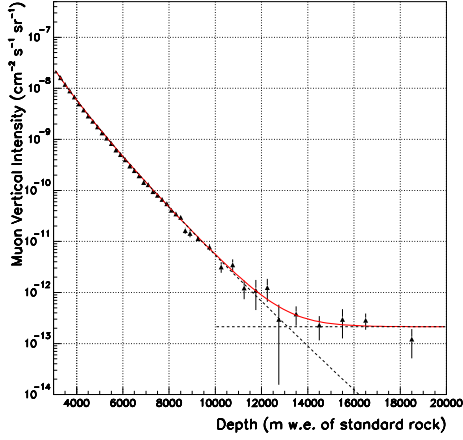


Figure 5: Vertical muon intensity as a function of the traversed slant depth in standard rock.

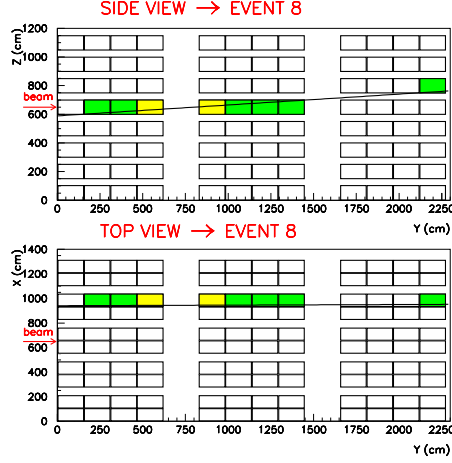


Figure 6: Top and side view of a typical CNGS event inside LVD: a muons originated by a CC ν_μ interaction in the rock upstream the LNGS.

References

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DISCUSSION

JIM BEALL: What distance did you use in the estimate of hundreds of events for a galactic SN ?

MARCO SELVI: We considered a SN core collapse at 10 kpc, close to the center of the galaxy (8.5 kpc).

JIM BEALL's Comment: I would like to underline that the continuous and continued operation of this detector is very important.